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ADAPTIVE CONTROL FOR ENERGY CONSERVATION

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OBJECTIVE

The objective of this project is to investigate the use of adaptive control techniques in heating, ventilating, and air conditioning (HVAC) systems in solar heated and cooled buildings to minimize the consumption of auxiliary energy. Optimal control theory is used in conjunction with the adaptive control techniques to accomplish the minimization of auxiliary energy. The resulting technique is referred to as adaptive optimal control (AOC).

BACKGROUND

Control of heating, ventilating, and air conditioning systems is often accomplished from the standpoint of building comfort; however, with the increased cost of energy and concern for energy conservation, it is of interest to attempt to control HVAC systems to insure building comfort with minimum energy usage. In relatively simple systems, such as single family residences, control strategies for minimizing energy usage are straightforward and can be designed intuitively; however, in most complex HVAC systems, such as one finds in large buildings, it is not clear that control strategies for minimizing energy usage can be deduced intuitively. This is especially true in systems with alternate energy sources or with energy storage such as in solar heated and cooled buildings.

This study has been made by computer simulation and is centered on the National Security and Resources Study Center (NSRSC), a large solar heated and cooled building at the Los Alamos Scientific Laboratory (LASL). Although the study is based on a specific building, the results are completely general. Simplified models of the building and HVAC system have been developed for both the heating and cooling modes. The control strategies actually used in the NSRSC were simulated in the models and an adaptive optimal controller was developed and also simulated. Simulation runs were made with both the conventional controller and the adaptive controller and performance results of the two simulations were compared. In the first results (obtained using a partial derivative system identification method), the adaptive optimal controller model demonstrated a savings in auxiliary energy of 28.8% for the heating simulation and 18.3% for the cooling simulation when compared to the conventional controller simulation models.

The basic technique is to identify a linearized model of the building and HVAC system, then employ optimal control theory to determine an optimal controller which maintains an appropriate room temperature while achieving minimum energy usage. The problem is couched in the form of a linear regulator. The actual building and HVAC system is a nonlinear system with operating points which can vary over a wide range. The linearized model is valid only about a region of the operating point; thus, the identification of a linearized model must be an on-going process with the optimal controller being modified or adapted for each new linearized model or operating point of the system.

The basic block diagram of the system with the adaptive optimal controller is shown in Fig. 1. The building or plant represents the nonlinear dynamics of the building and the entire HVAC system, which can be represented by a differential system of the form

$$\dot{x} = f(x,u,t) \qquad (1)$$

where x is the state vector containing such variables as room temperature and storage tank temperature, and u is the control vector containing such variables as flow rates. The model identification block represents a system identification process which generates a linear model that accurately reproduces the nonlinear plant behavior at the given operating point. Using the linearized model, the optimal gains and offsets are computed which the controller uses to generate the control signal u.

The linearized model is in the form

$$\Delta\dot{x} = A\Delta x + B\Delta u$$

Where

$$\Delta x = x - x_o \qquad (2)$$

and

$$\Delta u = u - u_o.$$

The variables x_o and u_o are the current operating points of the actual system.

The optimal gain computation block of Fig. 1 employs standard linear regulator theory with the addition of set points for both the control and state variables. The cost functional is given by

$$J = \frac{1}{2}\int_0^T [(x-x^*)^T Q(x-x^*) + (u-u^*)^T R(u-u^*)]dt \qquad (3)$$

where x* and u* are the set-points for the state and control vectors respectively.

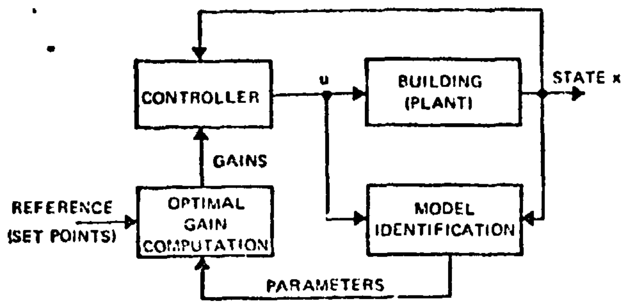

Fig. 1. Block diagram of adaptive optimal controller.

The Q and R matrices are weighting matrices which assign relative importance to the various state and control variables. A relatively large weight is assigned to the room temperature in Q to maintain appropriate comfort conditions and to the auxiliary energy in R to penalize auxiliary energy usage.

The control vector u is given by

$$u = \xi - K(x - x_0) + u^*. \qquad (4)$$

The computations for ξ and K are outlined in Publication 2. The approach basically uses a piecewise linear controller. The linearized model is determined and the gain matrix, K, and offset vector, , are computed at the beginning of a fixed adaptation interval. The gain matrix and offset vector are then unchanged over the adaptation interval until the beginning of the next adaptation interval when a new linearized model is determined and the control vectors are recomputed.

Schematics of the heating and cooling systems are shown in Fig. 2 and Fig. 3, respectively.

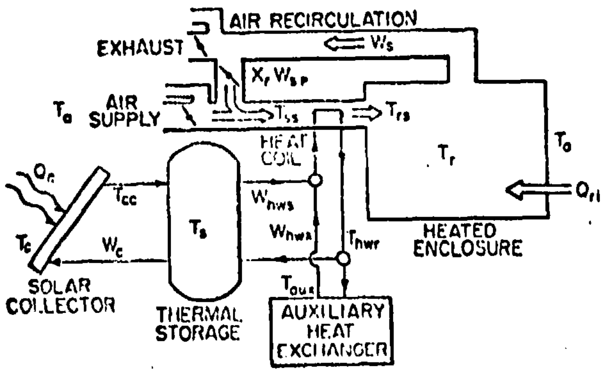

Fig. 2. Schematic of model used in solar heating simulation.

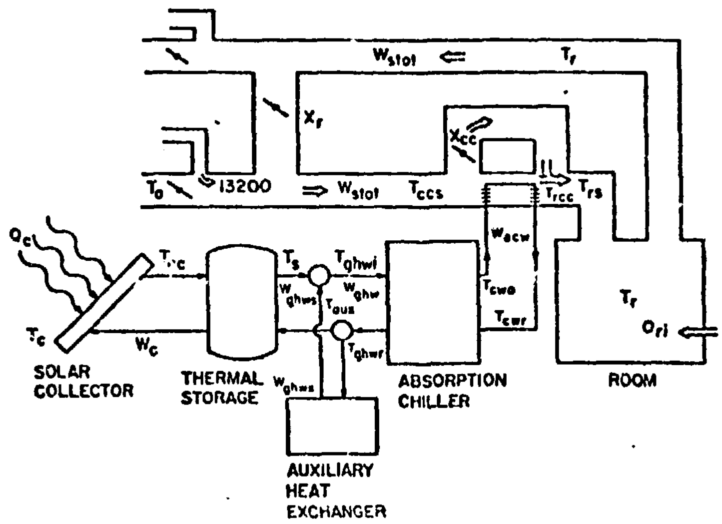

Fig. 3. Schematic of model used in solar cooling simulation.

SUMMARY

Accomplishments in the period covered by this report include completion of a nonlinear optimal control study to establish performance bounds and testing of a sequential least squares system identification procedure. The cooling model has yielded additional results and work has begun on upgrading of the heating model. A technique has been developed to optimally compute the set-points for the linear regulator, and a development in the adaptive optimal control strategy has been made which will enhance its potential for implementation. A conceptual investigation of the inherent capabilities of linear regulator controllers has shown them to have an inherent superiority. Several presentations of the ACC approach have been made.

TECHNICAL ACCOMPLISHMENTS

- A nonlinear optimal control study was conducted for the heating system of Fig. 2 to establish an upper bound on achievable performance. In this study, perfect knowledge of the weather parameters was assumed in order to investigate whether such advance knowledge can help control temperature in a more energy-conserving manner. Comparison of these results with those of previous adaptive control studies that did not assume such information imply that prior knowledge of weather conditions did not significantly aid in reducing auxiliary energy usage.

- A previously developed system identification technique using a sequential least squares approach was tested on the solar collector of the NSRSC. Difficulties were encountered that are believed to be attributable to the long time constants and consequent lack of spectral richness in the variables. Further investigations of the system identification technique will be made to overcome these difficulties.

•Modifications have been made in the controller for the cooling model of Fig. 3, and a savings in auxiliary energy of 20.2% has been demonstrated. This is considered an intermediate result and work in the cooling simulation will continue.

•Work has begun to upgrade the heating model. A second zone has been added so that the model represents a building with both an interior zone and a perimeter zone. The mass of the building has been added for both zones and the temperature of the mass in each zone has been defined as a state variable. Improvement and simplification of the collector model has begun and evaluation will be forthcoming soon. Similar upgrading will be done on the cooling model.

•A technique has been developed to compute the set-points for the system in an optimal fashion. Some of the set-points are specified for the system and not subject to computation. Room temperature is such a variable, although its set-point could be changed to achieve nighttime set-back. The other set-points are recomputed each time the adaptation takes place and this procedure yields an improvement in the auxiliary energy savings. This procedure may also solve the erratic behavior observed in the initial phases of the project when attempts were made to optimize the collector system along with the storage and the air-handling systems. Simulation results are presented in a subsequent paragraph.

•A development in the adaptation strategy of the adaptive optimal control technique has been made that will enhance its potential for implementation. The new technique will allow the use of a standard two-way valve in the storage/auxiliary heat exchanger supply lines instead of a more expensive proportional three-way valve. Simulation results are presented in a subsequent paragraph.

•A technique known as Interpretive Structural Modeling (ISM) has been used to analyze the inherent capabilities of conventional controllers and linear regulator controllers. Based on that analysis, the following conclusion is drawn:

> If performance is judged by the same measure in both systems, the use of more information plus the optimal computation of the linear regulator must yield better satisfaction of the performance index.

•Efforts to disseminate information about the AOC technique continue. An informal presentation of the AOC technique was made to members of the Control Theory and Application Committee of ASHRAE (TC1.4) at the Albuquerque meeting on June 27, 1978, and interactions with HVAC system controls manufacturers are underway.

•Recent simulation results that incorporate some of the developments described above are shown in Table 1. The "conventional controller" results embody control strategies designed for the NSRSC. The "standard adaptive" results are for the AOC procedure using the sequential least squares system identification technique. The "standard adaptive with set-point computations" uses the system identification technique and the technique for optimally computing set-points described above. The "standard adaptive with valve improvement" uses the system identification technique and the improvement to use a two-way valve described above, but does not use the optimal set-point computations.

SUMMARY OF RESULTS

	AUXILIARY ENERGY*	REDUCTION* %REDUCTION	SOLAR ENERGY COLLECTED*	ROOM TEMP AVERAGE	ROOM TEMP MAX MIN
CONVENTIONAL CONTROLLER	6.7460		3.1373 16.05%	70.02°F	70.37°F 69 [illegible]°F
STANDARD ADAPTIVE	4.0927	2.6533 39.33%	5.5481 28.38%	69.72°F	70.10°F 68.11°F
STANDARD ADAPTIVE WITH SET-POINT COMP	3.9118	2.8342 42.01%	5.6083 29.[illegible]%	69.58°F	70.17°F 67.08°F
STANDARD ADAPTIVE WITH VALVE IMPROVEMENT	3.2830	3.4630 51.33%	6.3720 32.60%	69.74°F	70.47°F 67.38°F

*10^6 BTU

TABLE 1

FUTURE ACTIVITIES

Planned activities for this project are summarized below:

•Complete the model upgrading for both the heating and cooling models.

•Apply the nonlinear optimal control approach to the upgraded models to firmly establish performance bounds.

•Simulate operation over extended periods and make parameter variation studies to thoroughly evaluate the AOC concept.

•Investigate implementation of the AOC concept in an actual building.

•If the investigation proves to be promising, implement the AOC concept in a building.

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